

EXPERIMENTAL VALIDATION OF MODELS APPLICABLE TO THE ULTRASONIC INSPECTION OF NUCLEAR COMPONENTS

B. P. Newberry, F.J. Margetan, and R. B. Thompson

Ames Laboratory
Iowa State University
Ames, IA 50011

INTRODUCTION

Achieving reliable inspection of nuclear reactor components requires the development and proper field implementation, of a variety of ultrasonic techniques. Because of advances in ultrasonic technology and concerns with ever changing potential failure modes of aging reactors, new inspection techniques are constantly undergoing development and validation. The cost of a purely experimental approach to this process can be excessive due to sample fabrication, measurement and data interpretation, and destructive analysis. Consequently, research efforts have been aimed at the development and application of models which will help reduce those costs by providing theoretical guidance [1,2]. Reported here are the results of an experimental program which was undertaken with the goal of determining the accuracy of the models in predicting inspection results. Two models were considered. The first predicts the evolution of ultrasonic field patterns as a beam propagates from a transducer and into a component. The second predicts the ultrasonic inspection response of a branched crack, which is an idealization of an intergranular stress corrosion crack (IGSCC).

BEAM MODEL

The Gauss-Hermite (GH) beam model is based on an expansion of the transducer radiation field in a complete set of orthonormal Gauss-Hermite functions, each of which individually satisfies the wave equation within the Fresnel approximation. In this manner, the radiation from a probe with general amplitude and phase distribution across its surface can be described. This diffraction theory has been combined with a ray tracing model to account for the refraction, focusing, and aberration effects which occur when the beam encounters a material interface. Consequently, the ultrasonic field produced in a part when inspected by a transducer coupled through a wedge or water bath can be predicted. Details of this model can be found in Refs. [2-4].

The experiments to validate this model were carried out in an immersion tank using a .25 inch diameter circular, unfocused broadband transducer with a nominal center frequency of 10MHz. The test specimen was a 1" thick rectangular block of fused quartz glass with properties; longitudinal wave-speed, $C_L = .597 \text{ cm}/\mu\text{s}$; shear wave-speed, $C_T = .376 \text{ cm}/\mu\text{s}$; and density

$\rho=2.2\text{gm/cm}^3$. This sample contained several air bubbles at various depths below the planar surface which were on the order of 200 microns in diameter. Beam profiles were obtained by scanning the probe past an air bubble and recording the pulse-echo response produced by the reflection from the bubble. By scanning at small increments and considering the bubble to be essentially a "point" reflector, very good resolution was achieved in mapping the beam profiles experimentally. Figure 1 shows a schematic of the experimental geometry. Since the Gauss-Hermite model predicts profiles for constant frequency waves, the experimental waveforms for each point in a scan were transformed using an FFT algorithm. The amplitude of a particular frequency component is then extracted and plotted versus position in the scan.

Beam profiles were mapped at refracted beam angles of 30, 45, 60 and 75 degrees for both longitudinal and shear waves. A longitudinal profile was measured at normal incidence as well. Due to space limitations, only a few representative profiles can be shown here. In the following figures, all of the amplitudes have been normalized so that the comparisons are of beam shape and not of absolute beam amplitude. The horizontal axis in the figures indicates position along the scan path with zero being the starting point, as shown in Fig. 1. Given with the figures is the value of the parameter S , which is a generalization of the standard nearfield to farfield transition parameter of a piston. Generally $S>1$ is considered farfield. One last important note is that the experimentally obtained beam profiles are the product of propagation of the ultrasound both to and from the reflector and are therefore not truly the beam profiles which exist on the solid. However, since the same transducer is being used as both transmitter and receiver, reciprocity implies that the beam profiles predicted by the Gauss-Hermite code need only be squared in order to make the comparison with the experimental data. Figure 2 shows the beam profiles for longitudinal waves at 10 MHz for angles of 45, 60 and 75°. Figure 3 shows the equivalent for shear waves. The agreement between the theory and experiment for both modes is good up to approximately 60°, however the longitudinal case is somewhat better than the shear case at this angle. The disagreement between the theory and experiment at angles higher than 60° is believed to be a limitation of the scalar nature of the model. The refraction and aberrations at these angles are severe enough that assumptions as to the smoothness of the wavefronts may not be applicable. This is consistent with the fact that the theory deteriorates at a slightly lower angle for shear waves since the scalar model is more restrictive for this mode. Overall, the effectiveness of the model in predicting the beam shape is quite excellent.

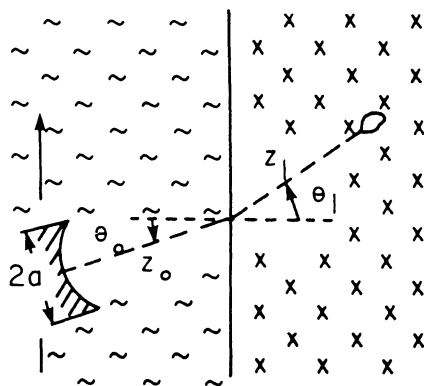


Fig. 1. Experimental geometry for beam mapping.

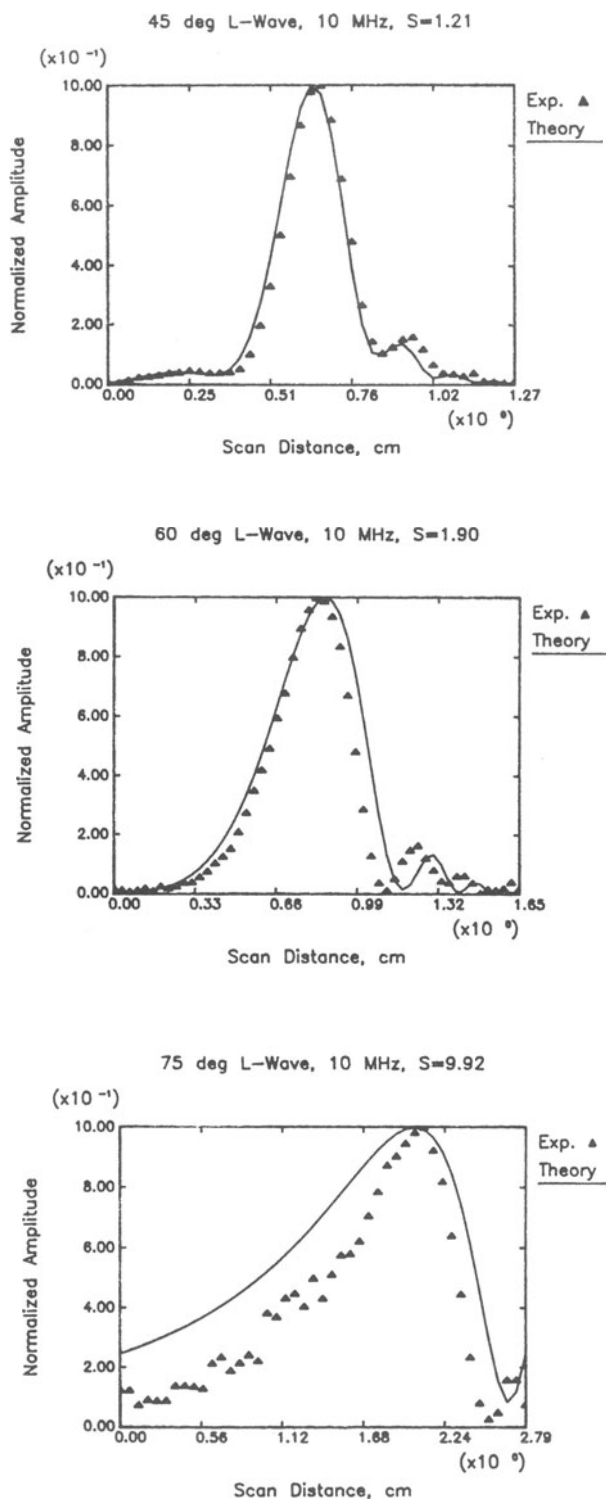


Fig. 2. Beam profiles at 10MHz for refracted longitudinal beams

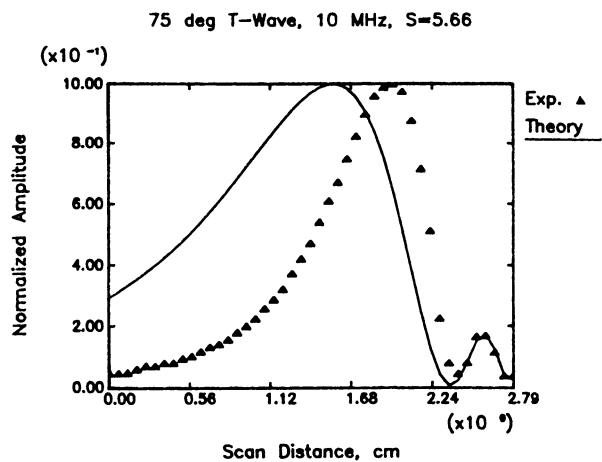
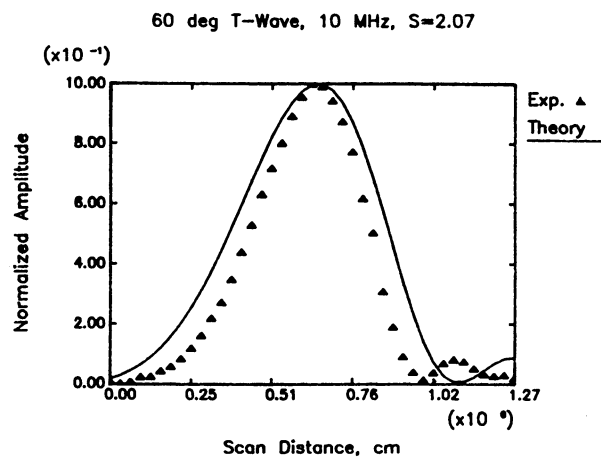
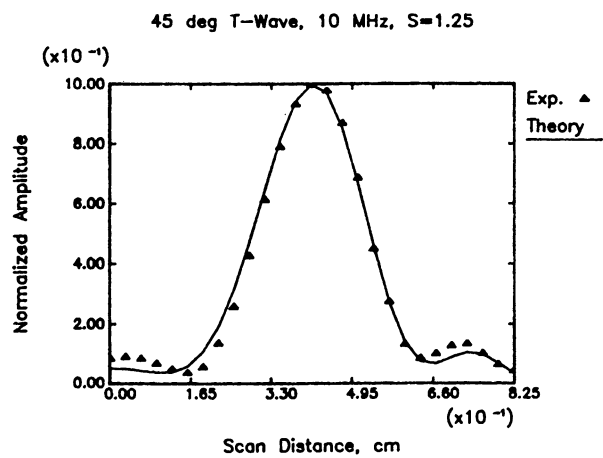


Fig. 3. Beam profiles at 10MHz for refracted shear beams

CRACK MODEL

The crack scattering model evolved as an attempt to model the response of an intergranular stress corrosion crack (IGSCC). The IGSCC has been modeled as a "Y-shaped" crack having a surface connected stem with branches having arbitrary length and angle. The crack is three-dimensional with the stem and branches being represented by truncated ellipses. The crack is assumed to be illuminated in the plane perpendicular to the crack mouth with a 45° shear wave beam of Gaussian cross-section. With the appropriate choice of initial width, the Gaussian beam can be used to model farfield piston radiation [5]. The scattering is predicted using the Kirchhoff approximation for perfect, stress free crack faces. Details of the crack model may be found in Ref. [2]. The results of the crack model, combined with an appropriate reference signal, can be used to predict time domain signals as they would appear on an oscilloscope during an inspection.

In order to evaluate this model, a flaw specimen was produced by a new powder metallurgical technique [6]. The specimen was a rectangular iron compact with properties: $C_L = .546\text{cm}/\mu\text{s}$, $C_T = .305\text{cm}/\mu\text{s}$, $\rho = 7.48\text{ gm}/\text{cm}^3$. The sample was 4 cm thick and contained a Y-crack with dimensions as shown in Fig. 4.

The sample was inspected in an immersion tank using a 0.5 inch diameter circular, unfocused transducer with nominal center frequency of 2.25 MHz. The transducer was positioned so as to excite a refracted shear wave beam of 45° in the sample through the upper surface. The transducer was scanned parallel to the upper surface, as shown in Fig. 4, and the pulse-echo signal reflected from the crack was recorded at incremental positions during the scan. The transducer was positioned so that the plane containing the incident and refracted angles was normal to the plane of the crack face and the beam was centered on the crack. The reference signal for this experiment was chosen to be a corner reflection from the end of the sample.

The results of a scan of the Y-crack are shown in Fig. 5. This figure presents each of the time domain waveforms acquired during the scan. These waveforms represent voltage amplitude versus time. The various waveforms are staggered in a waterfall pattern with the scan progressing from the bottom to the top of the figure. This figure allows the various signals

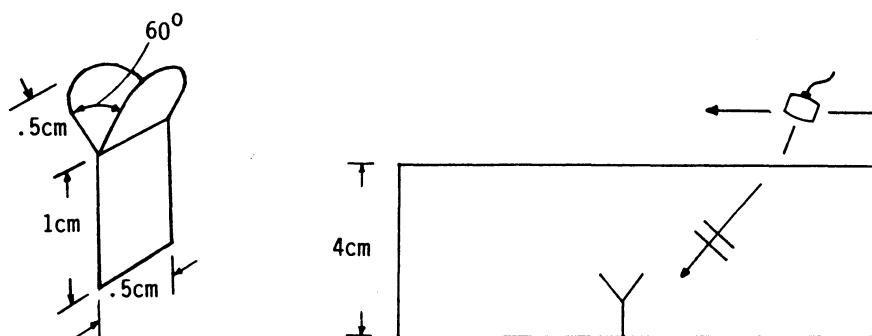


Fig. 4. Y-crack specimen and experiment

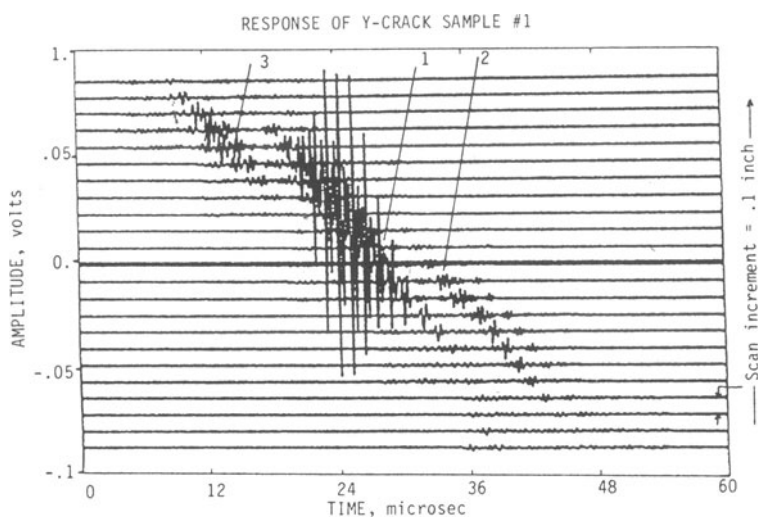


Fig. 5. Experimentally measured response of Y-crack

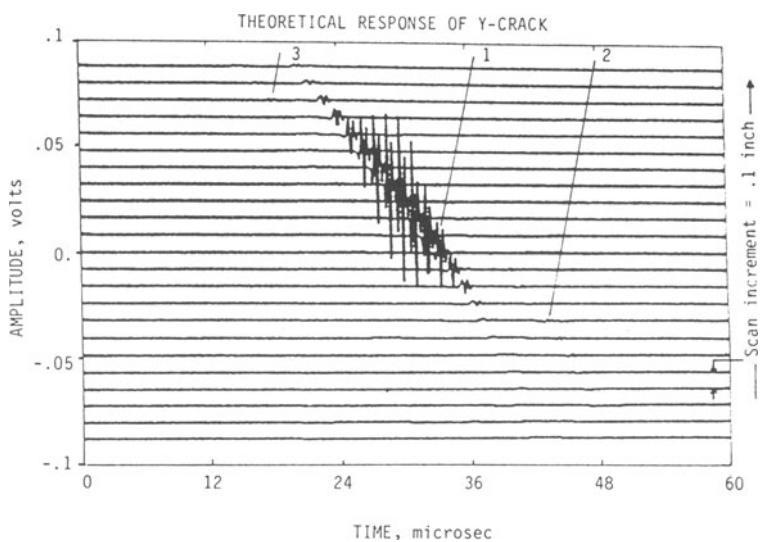


Fig. 6. Theoretically predicted response of Y-crack

reflected from the crack to be seen in the context of when they occur both spatially (at what point in the scan path) and temporally (with what time delay). Figure 6 presents the equivalent data as predicted by the model. In both figures, 3 main signals have been labeled. These are believed to correspond to the cases illustrated in Fig. 7. The times at which the signals occur, both spatially and temporally, as predicted by the model are in good agreement with the observed signals. Obviously, however, the amplitude of the signals are in disagreement. The peak amplitude of the corner signal [#1] for the experiment is about twice as great as for the model. This discrepancy is not fully understood since most of the problems which could possibly be associated with the crack specimen, such as roughness, contact of crack faces, or misorientation of the crack would tend to lower the experimentally observed amplitude rather than raise it. This would suggest that some aspect of the model is deficient. This point has not been fully resolved.

It is not surprising, however, that the signals #2 and #3 are relatively lower in amplitude in the theory as opposed to the experiment. The crack branches are not perpendicular to the incoming wave and consequently the reflection will be away from the transducer. This fact is reflected in the small predicted amplitudes. The larger experimental amplitudes are most probably due to roughness of the crack faces causing more diffuse scattering.

CONCLUSIONS

The Gauss-Hermite beam model appears to be a useful tool for predicting ultrasonic beam profiles which occur in materials during nondestructive inspection. This model has found application in probability of detection (POD) modeling [7], through transmission inspection modeling [8] and is being applied to problems such as wave propagation in anisotropic materials and prediction of surface geometry induced beam distortions. The Y-crack model has demonstrated a potential for predicting the response of branched cracks during an ultrasonic inspection. Some details of absolute amplitude prediction are still uncertain, but the model has the ability to appropriately predict the arrival of signals from various flaw features.

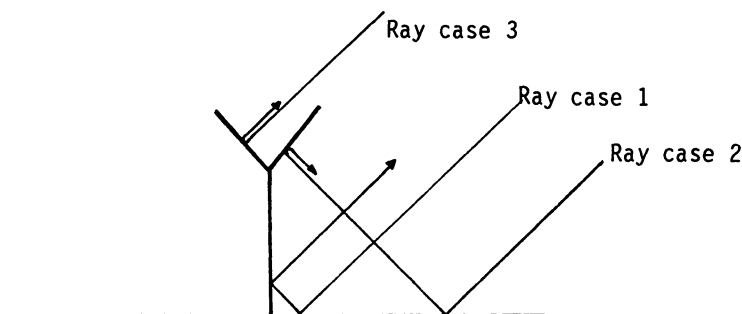


Fig. 7. Reflected signal cases for Y-crack.

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